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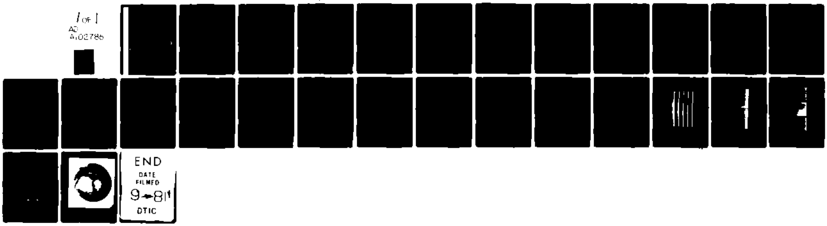

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The Control of Saturn's Kilometric Radio Emission by Dione

by

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May, 1981

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ABSTRACT

Observations of Saturn's kilometric radio emissions obtained by the Voyager 1 plasma wave receiver during the encounter of the Saturnian system in late 1980 reveal a strong but apparently transitory control by the orbital phase angle of Dione. At 56 kHz the effect of the Dione control is particularly evident during a two-week period centered roughly on closest approach. The intensity of the Saturnian emission is suppressed sharply when Dione is in the local dusk sector. We propose that the transitory nature of the Dione control is actually a geometric effect and that a time-variable plasma torus associated with Dione can explain most of the observed details of the Dione modulation by creating a shadow zone near the equatorial plane.

I. INTRODUCTION

The Voyager planetary radio astronomy investigation provided the first incontrovertible evidence of nonthermal radio emissions from Saturn[1]. The radiation spectrum peaks in the kilometer wavelength regime near 200 kHz and is apparently emitted from the northern hemisphere in the free-space R-X (right-hand, extraordinary) mode. Periodicities in the occurrence of the radio bursts have been analyzed to give an internal planetary rotation period of 10 hours, 39.9 minutes[2].

Further information on the morphology of the radio emissions was gained during the Voyager 1 Saturn flyby in November, 1980, which demonstrated that the radio emissions do not rotate with Saturn in a search-light-like fashion, but are pulsed at a particular Saturn rotation phase into a broad solid angle[3,4]. Observations of the radio emission at 56.2 kHz by the plasma wave instrument revealed a modulation of the intensity of the radio emission with a period very close to the orbital period of Dione indicating some control of the emission as a function of the orbital phase of the moon[3]. This control was also reported by the planetary radio astronomy investigation[4] with the maximum effect seen at lower frequencies[5], but extending as high as 200 kHz. The magnitude of the Dione influence is not constant in time and was strongest near closest approach.

It is the purpose of this paper to analyze the effect of Dione's orbital phase on the emission of radio waves from Saturn in order to explain the apparent transitory nature and suggest a mechanism for the interaction with the moon.

II. THE NATURE OF THE DIONE INFLUENCE

We begin this section with a brief description of the Saturnian kilometric radio spectrum below about 56 kHz which is the upper frequency limit of the plasma wave receiver. Fig. 1 is a typical event as seen by the plasma wave instrument as Voyager approached Saturn on November 11, 1980. Fig. 1 shows the amplitude of radio signals as a function of time for the upper 5 channels of the plasma wave spectrum analyzer. The instrumentation has been previously described[6]. Here, the height of the solid black area represents the average power flux (W m^{-2} Hz^{-1}) and the line above the averages gives the peak value during each of the 48-second averaging intervals.

The radio burst shown in Fig. 1 obviously increases in amplitude with increasing frequency to a peak above the frequency range of the instrument. The emission is highly time-variable, showing changes in amplitude of nearly an order of magnitude on time scales of a few minutes. While gross amplitude changes track fairly well from one channel to the next, many of the fine-scale features are totally uncorrelated with those of adjacent channels indicating narrowband elements in the spectrum. Hence, the temporal variations of the Saturnian kilometric radiation are similar in many respects to the auroral kilometric radiation from the Earth. The frequency of maximum emission amplitude for Saturnian kilometric radiation is near 200 kHz and the low frequency cutoff has been reported to be frequently near 60 kHz[1]; however, it is apparent from Fig. 1 that the emission is detectable at low levels at frequencies as low as 10 kHz. The peak of the event at all frequencies shown falls between $0° < \lambda_{SLS} \leq 135°$ where λ_{SLS} is the SLS longitude[2].

This paper deals specifically with the correlation between the orbital phase angle of Dione, ϕ_{Dione}, and the amplitude of the kilometric radio emission which was originally demonstrated by Gurnett et al.[3]. Fig. 7 of that paper shows a 16-day trace of the amplitude of the radio emission at 56.2 kHz as a function of time along with a plot of the Dione phase angle which showed that in addition to the 10 hour, 39.9 minute modulation related to Saturn's rotation, the emission was strongest when Dione was in the local dawn sector. Fig. 2 is a plot of the hourly average power flux of the radio emission at 56.2 kHz as a function of radial distance. Also plotted is a dashed line with a R^{-2} dependence. The arrows indicate times when $\phi_{Dione} = 270°$, that is, when Dione was at local dusk. It is clear from Fig. 2 that the effect of Dione is to suppress or attenuate the Saturnian radio emission when $\phi_{Dione} \approx 270°$. The peaks of the 10 hour, 39.9 minute bursts approximately follow a R^{-2} dependence except for periods within ~ 200 R_S when the amplitude of the peaks fall well below the curve coincident with the passage of Dione through the dusk sector. Hence a reinterpretation of Fig. 7 of Gurnett et al. is that the emission is suppressed when Dione is near local dusk. The Dione suppression might explain the apparent north-south asymmetry in the source strength at lower frequencies reported by Warwick et al.[4] in view of the fact that Dione was near local dusk for most of Voyager 1's trajectory through southern latitudes.

It was noted that the Dione control was most visible near closest approach and tended to disappear at large distances[3,4]. By analyzing traces similar to that in Fig. 7 of Gurnett et al.[3], and Fig. 2 of this paper, it is apparent that a clear signature is not present much before day 308 or after day 325 of 1980. These dates correspond to Voyager-Saturn distances of 227 and 165 R_S, respectively. To illustrate the transitory nature of the Dione effect, we show the result of a statistical study of the occurrence of kilometric radiation as a function of Dione's orbital phase angle. The bar graphs in each of the three panels of Fig. 3 show the power flux below which 98 percent of the samples fell for each of 12 phase angle bins. Recall that phase angle is measured positive eastward from a plane containing Saturn's rotation axis and the Sun, with 0° at local midnight. The center panel includes all data covered by Fig. 7 of Gurnett et al.[3] when the Dione effect is qualitatively most apparent. The first and third panels present results from the inbound and outbound legs when little or no Dione control was apparent. It is clear the distant inbound and outbound data show no significant trend as a function of Dione phase angle. On the other hand, the difference in amplitude at the 98th percentile level between phase angles near 90° and 270° is about two orders of magnitude for the period near closest approach.

It is clear that Dione plays an important role in determining the amplitude of radio emissions from Saturn detected by Voyager 1 at 56.2 kHz for about a two week period roughly centered on a closest approach. In the next section we shall discuss possible explanations for the time-variable nature of the Dione effect and also suggest mechanisms by which Dione might influence the emissions.

III. DISCUSSION

When considering the interactions by which a moon may influence the generation of magnetospheric radio emissions it is clear there are many possibilities. With the limited data available at this time it is unlikely that one explanation can be demonstrated to be superior to all others. We shall attempt, however, to explore a broad spectrum of mechanisms and hope to narrow the list of likely candidates to one or two which are consistent with all or more of the observations.

Our first task is to explain the transitory nature of the effect. That is, why is the effect seen only for about a two week period? A truly transient process which is active for two weeks and then inactive for long periods of time requires a mechanism by which to stimulate the control. Further, the long term studies show no Dione effect[4] so the active periods must be quite rare. Hence, it is strange that the effect was seen coincidently with closest approach and we shall argue that the effect is not transitory but dependent on the location of the observer.

The primary factor which changes coincidently with the encounter is the geometry of the observations. Clearly, radial distance cannot be important, since the waves are freely propagating and temporal variations at the source will be directly observable at any distance the emission itself is observable. Other parameters which minimize near encounter are latitude and the distance from Saturn's equatorial plane. At large distances on the inbound leg, Voyager 1 is at about

8.4° latitude and it leaves at about 26° during the outbound portion of the trajectory. Hence, close to Saturn, the trajectory crosses the equator twice and the distance from the equator is small for all of the near-encounter pass.

We suggest the simplest explanation of the transitory nature of the Dione control is actually geometric in nature and specifically related to the low latitude or small distance from the equatorial plane of Saturn during the two weeks around closest approach. The effect became apparent around day 308 when Voyager 1 was at 8.3° latitude and about 33 R_S above the equatorial plane. On day 325, when the effect apparently disappeared, the spacecraft was at a latitude of 25.4° and 71 R_S above the equatorial plane.

In the discussion which follows we assume the source of Saturn's kilometric radiation is at relatively low altitudes on high latitude field lines, presumably in the auroral region. Warwick et al.[4] presented observations of a polarization reversal as Voyager 1 moved from northern to southern latitudes which strongly suggest a source located near the polar region. In addition, the temporal character of the emission as shown in Fig. 1 is extremely similar to that of auroral kilometric radiation at the Earth and broadband kilometric and decametric radiation at Jupiter, all of which are believed to be generated in the auroral region of the respective planet. In fact, continuum radiation (including narrowband kilometric radiation at Jupiter) is the only known planetary radio emission thought to be generated near the equator[7]. Hence, we consider an equatorial source location for Saturn's kilometric radiation to be extremely unlikely.

Fig. 2 demonstrated that the effect of Dione was to attenuate the Saturnian radio emission as opposed to stimulate or amplify it. The attenuation could be caused either by a propagation effect or by a basic change in the source, itself. In either case, the most likely interaction mechanism is a change in magnetospheric density associated with the satellite. A decrease in density could only be accomplished via a sweep-up effect and this is hardly a time variable process capable of disturbing the inner magnetosphere on time scales of a few days. An increase in magnetospheric density, however, could be the result of a process which liberates particles from the moon making the moon a plasma source. This type of process is known to be in effect in the Jovian system with Io being the primary source of plasma.

Frank et al.[8] argued that Dione should be considered a reasonable source for an oxygen torus at Saturn. A peak in the ion density at Dione's orbit with density and temperature profiles reminiscent of those at Io in Jupiter's magnetosphere suggests Dione, like Io, is a plasma source. Frank et al. also point out that the water ice or frost surface of Dione opens the possibility of plasma production via dissociation and ionization. These processes will be examined more closely below. A ledge-like structure in the plasma torus near Dione's L-shell has been reported by Bridge et al.[9]. Similarities of this structure with that observed at Io in Jupiter's magnetosphere are suggestive of a plasma source at Dione. Evidence from the Pioneer 11 magnetometer[10] may also be suggestive of a process involving plasma production at Dione. On the inbound Pioneer trajectory, a significant magnetic field perturbation was seen at Dione's L-shell. No effect was observed on the outbound leg. The local time of Dione was ~ 21 hours (φ_{Dione} ~ 315°) and ~ 1 hour (φ_{Dione} ~ 15°) for the Pioneer inbound and outbound Dione L-shell crossing, respectively. Although there are several possible explanations, this magnetic field signature is consistent with a ring current associated with Dione which varies with φ_{Dione}.

An increase in magnetospheric density could affect radio emissions either by modifying the propagation of the waves via refraction or reflection. There is some evidence that the Earth's auroral kilometric radiation is quenched by increasing the density in the source region[11], however, Gurnett and Anderson[12] have stated that although raising the density in the source might quench the emission, this result is not very likely. Another difficulty with direct modification of the source is that the plasma produced at Dione would have to have easy access to the source. That is, if the radio source were in the auroral region, it is unlikely that an equatorial plasma source at L ~ 6 could effectively modify the density in the auroral zone.

The alternative is to assume that an increase in plasma density associated with Dione affects the propagation of radio waves. Fig. 4 is a schematic representation of how a high density torus associated with Dione might affect the propagation of radio waves from Saturn. We have taken the model torus from Gurnett et al.[3], although the model shown by Bridge et al.[9] would result in essentially the same effect. Waves with frequency less than or equal to the local plasma frequency in the torus cannot penetrate the torus. Waves of higher frequency will be refracted away from the equatorial region, although the effect will diminish with increasing frequency.

There are many observations which suggest the model shown in Fig. 4 is viable. First, the density of the plasma torus as measured by both Pioneer 11[8] and Voyager 1[3,9] is on the order of 40 cm^{-3}. This corresponds to a plasma frequency of 57 kHz and a plasma of this density would be impenetrable by radio waves at 56 kHz and significant refraction would occur for waves well above 100 kHz. A refraction effect of this type is consistent with the frequency dependence of the Dione effect reported by Desch and Kaiser[5], since lower frequencies tend to be refracted the most. Second, because preliminary observations[3,9] suggest the plasma is confined near the equator, waves propagating near low latitudes would be most affected. Therefore, we expect a low-latitude shadow zone as was found at Jupiter for the Jovian kilometric radiation[13]. A shadow zone near the equator would explain the presence of a Dione control only near encounter when Voyager 1 was close to the equator. The asymmetry in the latitude at which the effect appears and disappears could well be a local time asymmetry in the thickness or density of the torus.

The remaining question is how does the orbital phase angle of Dione modulate the emission. The attenuation effect is only present when Dione is near local dusk. Why does the torus shadow the equatorial zone for only part of Dione's orbit? It is important to first establish that the effect of the torus is longitudinally symmetric. The evidence is embodied in Fig. 7 of Gurnett et al.[3] and Fig. 2 of this paper. Note that the phase of the Dione effect did not change as Voyager moved from near local noon before encounter to local early morning after the encounter. If there were a localized cloud of plasma which orbited Saturn, a phase shift would have been apparent as the viewing vantage point changed. Since the phase of the modulation did not change, the modulation effect must be longitudinally symmetric. This longitudinal symmetry should be fairly easily satisfied as a result of the rapid corotation of the plasma which will quickly distribute plasma in longitude even though the source may be localized.

In order to explain the dependence of the torus density on the orbital phase angle of Dione, we suggest that Dione may only be a plasma source when it is near local dusk. Hence, the plasma cloud produced dissipates on a time scale of about a day so that by the time Dione is near local dawn the torus density has decreased by a factor of say, two. Since the trailing hemisphere of Dione is always the same, it is not possible to argue for a hemispheric asymmetry in direct particle sputtering processes to explain the dawn-dusk asymmetry. On the other hand, there are obvious asymmetries in the surface features of Dione. Fig. 5 is an image of Dione taken by Voyager 1 when Dione was near local dusk. The hemisphere shown is the trailing hemisphere which features a complex pattern of wispy features. The wisps do not appear on the opposite hemisphere of Dione. Smith et al.[14] suggest the bright markings are controlled by a great regional system of fractures or faults possibly formed or reopened by internally generated stresses. The bright material is probably water ice which may be evidence of the escape of volatiles from within the interior of Dione. It is tempting, then to speculate that this relatively fresh surface frost is photosputtered when the trailing hemisphere is sunlit as it is when Dione is near local dusk, or that photodissociated volatiles produce the plasma.

Carlson[15] and Frank et al.[8] have discussed the rings as possible sources of plasma in the Saturnian magnetosphere. Of processes such as photosputtering, ion sputtering, sublimation with subsequent photodissociation, and others, photosputtering seems to be the most efficient mechanism. Photosputtering would be a convenient mechanism for an orbital phase dependent source of plasma at Dione in view of the hemispherical asymmetry of the wispy features shown in Fig. 5. Taking the hydrogen atom flux derived by Carlson[15] of $\sim 10^{8} cm^{-2} s^{-1}$, Dione can produce $\sim 10^{24}$ atoms s^{-1} (assuming the entire sunlit hemisphere is a source and the process of photosputtering is applicable to Dione). If the time scales for both creation and dissipation of the plasma torus is ~ 1 day (in order to provide a 2.74-day modulation period), then the production/loss rate must be on the order of $10^{28} s^{-1}$. We have assumed a torus 4 R_S thick, centered at 6 R_S, which fluctuates between 20 and 40 cm^{-3}. Obviously, photosputtering is not sufficient to produce a dense torus on the time scale of a day.

If we assume that the other processes considered by Carlson are no more efficient than photosputtering, we must consider a mechanism which is based on the release of volatiles from fractures in Dione's crust and subsequent photodissociation. Presumably the volatiles would be released into the exosphere at a constant rate but preferentially from the wispy hemisphere. However, photodissociation of the molecules would occur only during the dusk sector of Dione's orbit when the wisps are sunlit. This mechanism is largely speculative and production rates are dependent on the rate of volatile release, the type of volatile, and the photodissociation rate. It is comforting, however, that the injection rate at Io has been estimated[16] to be $2 \times 10^{29\pm1}$ ions s^{-1}, hence, as much as 200 times that required at Dione.

The proposed fluctuating torus model also requires a dissipation rate on the order of $10^{28} s^{-1}$. Richardson et al.[16] point out that outward radial diffusion via flux-tube interchange is the predominant loss mechanism at Jupiter and given that oxygen or some other heavy ion is an important constituent of the Dione torus[8,9] the centrifugally-driven interchange instability is likely to be important at Saturn, also.

Other possibilities exist to explain the transient Dione effect. For example, we have considered an auroral source location for the radio emissions in analogy to the case for both terrestrial kilometric radiation and decametric radiation at Jupiter. If one assumes an equatorial source in the torus, other mechanisms could be considered. However, if the source is near the equator, the equatorial shadow zone model becomes difficult to defend and a purely transient Dione effect coincident with the Voyager 1 encounter must be explained.

We have arrived at a scenario which is similar in part to effects observed at Jupiter. We propose that Dione is responsible for the production of plasma when it is near local dusk which forms a longitudinally symmetric torus. The torus then casts a radio shadow on low latitudes so that the Saturnian radio emission cannot be seen by a spacecraft near the equator. The torus decays with a time constant of about one day so that as Dione approaches local dawn the usual Saturnian emission reappears.

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FIGURE CAPTIONS

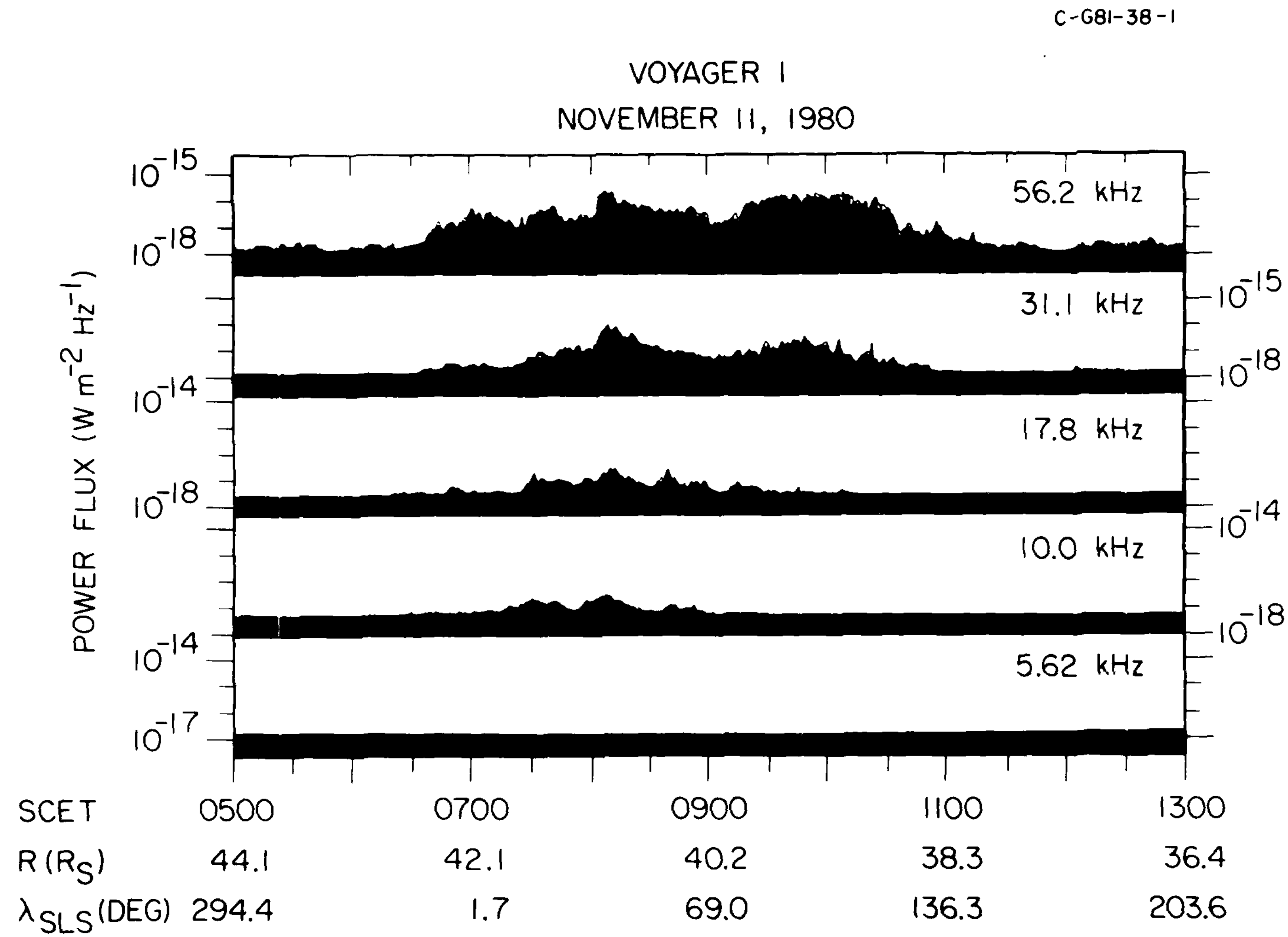
Figure 1 A typical example of Saturnian kilometric radiation extending from near 10 kHz to above 56 kHz. The most intense emission is detected when Voyager is between 0 and 135° SLS longitude.

Figure 2 A plot of hourly average values of the 56.2 kHz plasma wave receiver channel as a function of radial distance from Saturn. The narrow bursts are emitted at a period of ~ 10 hours, 39.9 minutes and generally rise in amplitude with decreasing R approximately as R^{-2}. The arrows indicate times when Dione is at local dusk and correspond closely to periods when there is little or no radio emission.

Figure 3 Plots of the 98th percentile amplitude as a function of Dione's orbital phase angle for the distant inbound, near encounter, and distant outbound Voyager 1 trajectories at 56.2 kHz. Notice the strong Dione control near encounter and the complete lack thereof during the distant inbound and outbound passes.

Figure 4 A schematic representation of how a Dione-related torus would refract radio waves from Saturn away from the equatorial region. A similar effect was found for broadband kilometric radiation from Jupiter.

Figure 5 An image of the trailing hemisphere of Dione taken by Voyager 1 when Dione was near local dusk. Note that this sunlit hemisphere is dominated by bright wispy features which are likely to be fresh outcroppings of water ice or frost. It is suggested the frost may be a source of plasma for a torus whose density fluctuates with the same period as Dione's orbit.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NOVEMBER 11, 1980
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10^{-18}
10^{-14}
10^{-18}
10^{-14}
10^{-17}
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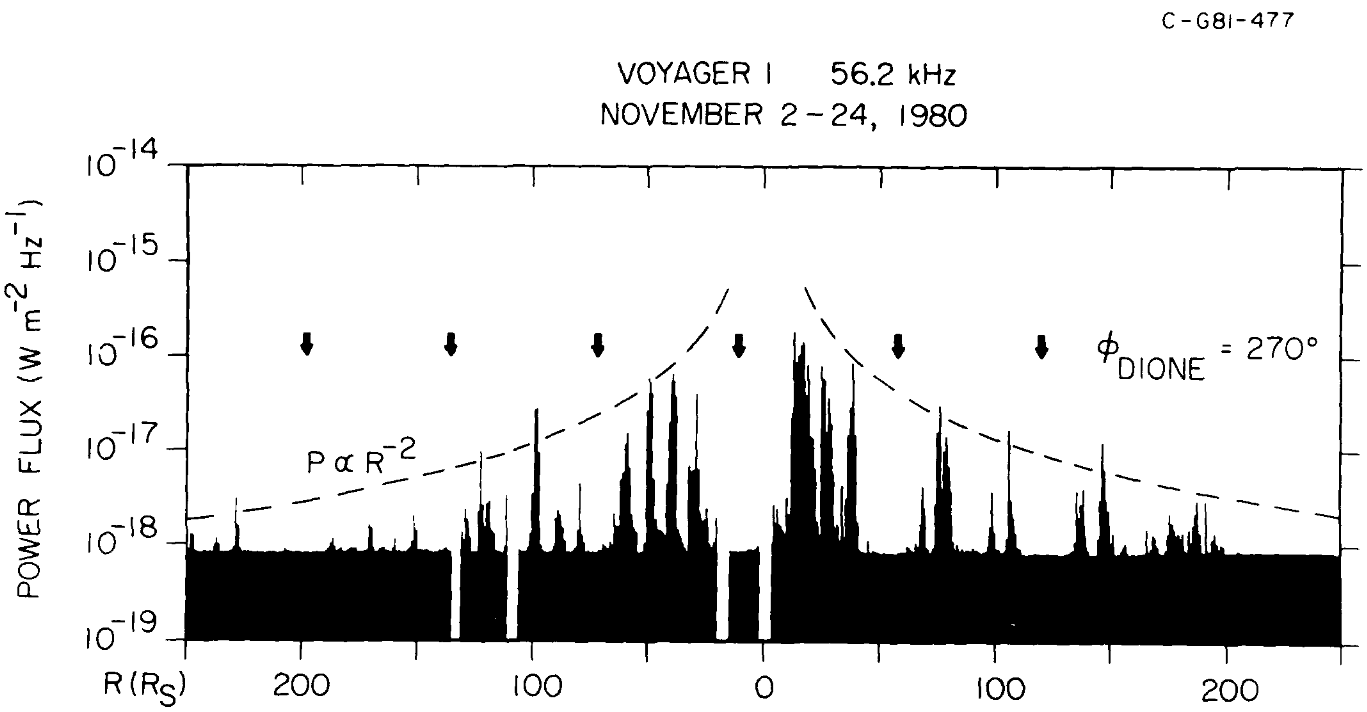
Figure 1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NOVEMBER 2-24, 1980
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10^{-16}
10^{-17}
10^{-18}
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100
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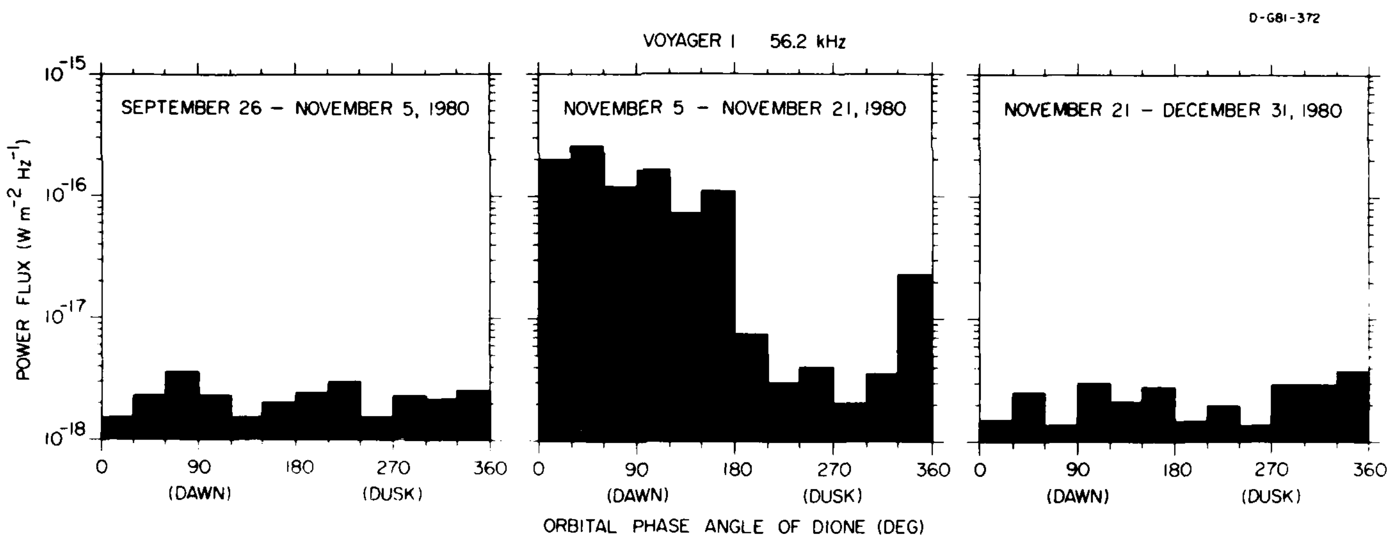
P $\propto$ R^{-2}
ϕ_{DIONE} = 270°

Figure 2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NOVEMBER 21 – DECEMBER 31, 1980
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180
270
360
(DAWN)
(DUSK)
ORBITAL PHASE ANGLE OF DIONE (DEG)

Figure 3

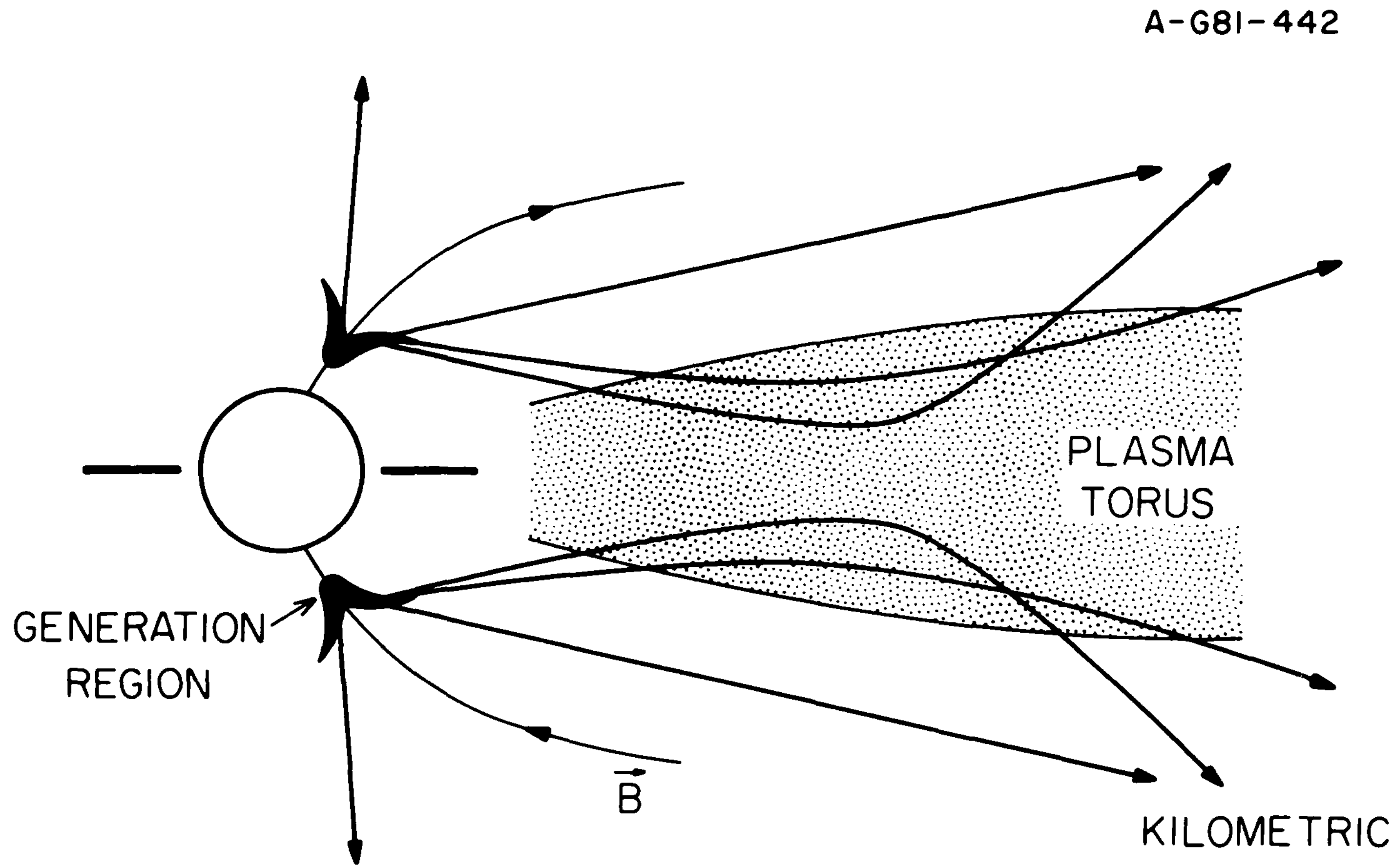
A-G81-442
PLASMA
TORUS
GENERATION
REGION
$\vec{B}$
KILOMETRIC
RADIATION

Figure 4

Figure 5

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